THE WEAKNESS OF C IV ABSORBER CLUSTERING IN KECK HIRES SPECTRA OF ADJACENT QSO SIGHTLINES[1]

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ABSTRACT

We observe with Keck/HIRES the $z \approx 2.5$ QSO triplet 1623+27 in order to explore on the scale of a Megaparsec the spatial clustering of C IV absorbers between adjacent sightlines. We find this signal to be significantly weaker than the clustering in velocity on corresponding scales along single sightlines, assuming that the relative velocity of absorbers is dominated by the Hubble flow. This indicates that small-scale clustering (200 km s$^{-1} < \Delta v <$ 600 km s^{-1}) of the C IV absorbers cannot be interpreted in terms of the positions of the absorbers in space, but must be considered as internal motions within individual absorbers, or within clusters of absorbers whose internal velocities dominate over Hubble expansion across the cluster scale. If the single-sightline signal is due to spatial clustering, it is caused by absorber clusters smaller than would be implied by their velocities if a Hubble flow is assumed. The spatial clustering of C IV absorbers at $z \approx 2$ is consistent with data on Ly α forest clustering measured in the same way at the same redshifts. However, present-day galaxy clustering, evolved back to $z \approx 2$, is consistent with C IV spatial clustering but perhaps not with that of the Ly α forest. Even so, one cannot as yet distinguish the two absorber populations on the basis of spatial clustering on these small scales.

Subject headings:

1. INTRODUCTION

One of the hallmark distinctions between QSO absorption systems containing strong C IV lines and those which do not has been, since early in the history of their study, the difference in clustering between the two populations as seen along single lines of sight. The Ly α forest has always been shown to be weakly clustered compared to C IV absorbers (Webb 1987, Hu et al. 1995, Chernomordik 1995, Cristiani et al. 1995), and perhaps not detectably clustered at all (Sargent et al. 1980, Rauch et al. 1992, Lu et al. 1996, Kirkman & Tytler 1997). In contrast, even early studies showed that C IV absorbers cluster significant in velocity along single sightlines (Young et al. 1982), with perhaps the best evidence coming from a large compilation of QSO spectra at approximately 100 km s^{-1} resolution (Sargent et al. 1988, hereafter SSB). This is usually described by the two-point correlation function ξ which equals the excess number of absorbers over random expectation found at a certain location with respect to a given absorber, usually quantified as a spatial or velocity separation between the two locations (and with ξ normalized by dividing by the random expectation). Depending on the sample selected, for line-of-sight velocity differences Δv of 200-600 km s^{-1}, values of ξ for C IV absorbers were found with $\xi \approx 10$ or larger.

Similar behavior is found in large C IV samples at spectral resolution higher than that of SSB e.g. within the largest clustering sample, 10 sightlines at 18 to 40 km s^{-1} FWHM resolution, analyzed by Petitjean and Bergeron (1994 - PB). (Other recent works at even higher resolution are based on even fewer sightlines: Songaila & Cowie 1996, Fernández-Soto et al. 1996, Rauch et al. 1996.) PB, like SSB, find an average $\xi \approx 10$ for Δv = 200-600 km s^{-1}, dominated by a broad, slowly declining component. (Specifically, they fit ξ with two components, of widths σ_v = 109 and 525 km s^{-1}, with the broader component containing 71% of the pair count over 30-1000 km s^{-1} and 93% over 200-600 km s^{-1}.) In contrast, even in those papers which found some clustering in

the Ly α forest, also on approximately these Δv scales or slightly smaller, the signal rarely exceeded $\xi \approx 1$. This is seen as clear evidence for a difference between these population, possibly implying distinct origins for the two.

There are caveats to this interpretation which suggest caution in comparing the single-sightline ξ values of the Ly α forest and C IV absorber populations. First, it is possible that single-sightline velocity splittings might arise from internal motions within absorbers, in which case the differences between the two populations' single-sightline ξ functions are not clearly tied to their spatial clustering behavior. SSB argue that, for C IV absorption arising in galaxy haloes, these velocity splittings cannot be due to gravitational orbits within these haloes, and clustering still contributes the dominant portion of the observed ξ on scales larger than $\Delta v = 200$ km s^{-1}. Indeed, many papers have modeled QSO absorption-line clustering in terms of spatial separations indicated by their relative velocities, whereas for highly over-dense structures, large differences between velocity clustering and spatial clustering become apparent e.g. Kaiser (1997). Models have been proposed, however, where non-gravitational acceleration might lead to splittings with large Δv (York et al. 1986).

Second, the intrinsic width of Ly α lines, up to $b \approx 60$ km s^{-1}, is much higher than for C IV because of thermal broadening, and significant on the scale of the clustering in Δv being discussed. Line-of-sight blending of Ly α lines does seem to obscure some of the clustering power seen in their corresponding C IV lines Fernández-Soto et al. (1996).

One way to assess the importance of such effects is to study the clustering of absorbers in adjacent sightlines close enough together so that the angular separation between them is less than or comparable to the velocity scales where clustering is seen or sought in single sightlines, here assuming that a Hubble expansion law at high redshift can be used to relate Δv and transverse separation. This addresses all of the above concerns. First, purely

internal velocity splittings cannot shift absorbers to a different sightline, and, second, blending cannot eliminate all of the small Δv absorber pairs that would otherwise exist between sightlines. Even if blending decreases or splittings increase the number of close absorbers pairs between sightlines, there is much less effect on ξ because these effects also change the total numbers of pairs used to normalize ξ. If all absorbers in a population are equally likely to cluster i.e. if all within a population cluster in a way described purely by the same ξ, the effects of blending or line splitting on close pairs and distant pairs cancel.

The 1623+27 QSO triplet discovered by Sramek and Weedman (1978) and has been used to measure the spatial two-point correlation function (here also denoted by ξ) of Ly α absorbers (Crotts 1989, Crotts & Fang 1996, with some members of the triplet also observed by Sargent et al. 1982, and SSB). We have obtained Keck HIRES spectra of these three QSOs, yielding a sample of C IV absorbers large enough and unambiguous enough that a useful comparison of spatial C IV clustering can be made to Ly α clustering and single-sightline C IV clustering. These C IV clustering results are rather different from prior results from single sightlines alone, which changes our understanding of clustering at high redshift.

2. Observations and Analysis

On the night of 20 May 1996, we used the HIRES spectrograph (Vogt 1994) on the Keck-1 10m telescope to obtain spectra of the QSO triplet Q1623+27. Each of the QSOs was observed with the same setup, providing wavelength coverage from 3872 to 6299Å. The observations were performed sequentially over a four hour period, and the spectrograph was not moved between observations. We exposed for 5400s on both Q1623.7+268A (KP 76, V = 18.4, z_{em} = 2.467) and Q1623.9+268 (KP 78, V = 19.4, z_{em} = 2.607), and 3000s on Q1623.7+268B (KP 77, V = 17.0, z_{em} = 2.521). The exposures were taken with a

$1.14'' \times 7.0''$ slit, which gave a resolution of 8 km s^{-1} and adequate sky coverage. The images were processed and the spectra were optimally extracted using an automated routine specifically designed by T. A. Barlow for HIRES spectra. The routine performs baseline subtraction, bias and flat-field corrections, and utilizes a bright standard star to trace the echelle orders and define the apertures for extraction. Thorium-Argon lamp images were obtained immediately after the observations to provide wavelength calibrations in each echelle order. The root-mean-square residuals in the wavelength calibration for each echelle order was less than 0.3 km s^{-1}. All wavelengths are vacuum values in the heliocentric frame. Each echelle order was continuum fit with a legendre polynomial to normalize the unabsorbed QSO flux level to unity.

As an example of these data, we present Figure 1, which shows a particularly complex C IV doublet from the faintest QSO, KP 78, fit by 10 components. The positions of components and best fit flux from VPFIT (Carswell et al. 1992) were determined; seen in Figure 1 for the $z \approx 2.24$ system, along with the continuum fit. The spectrum does not have useful SNR in the blue, where the correcponding Lya lines lie.

The redshifts of C IV doublets found in these data are listed in Table 1. We include only those redward of the Ly α forest, and list them according to the 200 km s^{-1} "blended" sample treated below. In comparison, the Crotts and Fang (1997) $\Delta\lambda \approx 1.5$Å KPNO 4m sample contains within this redshift interval the two stronger C IV doublets in KP 76, all of the KP 77 sample (with 1.878027 and 1.880660 blended together), and all of the KP 78 sample except 2.115063, with 2.061465 listed as uncertain. Their uncertain system at $z = 2.40602$ KP 77 appears to be a misinterpretation of the confused region of C IV and Mg II doublets near 5280Å.

3. Results

Sightline cross-correlating pairs for all C IV systems results in 36 in the first bin ($\Delta v < 500$ km s^{-1}), compared to the random expectation from a linear fit over the first 20000 km s^{-1} of 18.95 ± 6.71 for the first 500 km s^{-1} bin. These counts are obviously highly non-Poisson, so we do not assign an error estimate to the resulting two point function of $\xi(\Delta v < 500$ km s$^{-1}) = 0.90$.

It is more reasonable to consider merging C IV redshifts close to each other in the same sightline, since it seems likely that these are multiple representatives of the same absorber. If we over-correct for this effect, we do not damage the cross-sightline ξ, since blending together systems does not reduce the fraction of pairs between sightlines due to close cross-sightline Δv values, compared to the total number of cross pairs. We choose to blend together all systems in the same sightline within 200 km s^{-1} of each other, starting with the smallest splitting first. This is the same criterion adopted by SSB, so it leads to a direct comparison. The cross correlation of this sample (and samples defined by further criteria) are shown in Figure 2.

In correspondence with SSB, we reduce the sample to only those systems which would likely have been detected by their survey. This is a heterogeneous selection in terms of rest equivalent width W_o, and corresponds roughly to $W_o = 0.1$Å for their "Sample A2" (which also excludes all absorbers within 5000 km s^{-1} of the emission-line redshift. A homogeneous sample in W_o requires a cut at 0.15Å (their sample "A4," also with $\beta c >$5000 km s^{-1}).

The randomly expected number of pairs in the first 500 km s^{-1} bin for each of these subsamples ("Blended," "A2," and "A4") are 2.37 ± 0.57, 1.69 ± 0.49, and 1.07 ± 0.32, respectively, whereas the actually observed number of pairs in the first bin for each sample is 4, 1 and 0, respectively, leading to ξ values of $0.68^{+1.34}_{-0.52}$, $-0.41^{+1.39}_{-0.57}$, and $-1^{+1.75}_{-0}$, respectively. (These are 68% confidence intervals, corresponding to $\pm 1\sigma$, assuming Poisson errors in pair

counts, which is close to correct.)

4. Discussion and Conclusions

At $z = 2.15$ (and for $q_o = 1/2$) the transverse separations between the three QSOs correspond to velocities in the Hubble flow of 286 to 399 km s^{-1}. (For $q_o = 0.1$ they are 0.95 times smaller.) Therefore, structure dominated by the Hubble flow over 200 to 600 km s^{-1} would contribute to clustering on these scales, and correspond to proper separations of 0.36 to 1.07 h^{-1} Mpc. Since separations between the sightlines are smaller than this (0.51 to 0.71 h^{-1} Mpc), one must add a perpendicular (line of sight) velocity component up to about 500 km s^{-1} (although more typically about 200 km s^{-1}). Correlational activity from such a signal should be restricted to the first 500 km s^{-1} bin in Figure 2.

Nevertheless, the single sightlines over 200-600 km s^{-1} and the multiple sightlines for $v < 500$ km s^{-1} probe slightly different volumes around each absorber. We can evaluate the importance of the different sampling regions by considering the analytic fit by PB to the number of pairs in these velocity intervals. They find that the number of pairs is well-approximated by the sum of two gaussians, with standard-deviation velocity widths of 109 and 525 km s^{-1}, and with the wider gaussian contributing 30% of the number of pairs to the sum of the gaussians at their peak at zero velocity. When we integrate this distribution over the SSB sampling volume covering 200-600 km s^{-1}, we find 1.15 times as many pairs as when we integrate over the triple-sightline sampling volume. This is a relatively minor effect which we neglect hereafter, but one which tends to lower slightly the discrepancy we discuss below.

The actual value seen by SSB for the A2 sample is $\xi(200-600 \text{ km s}^{-1}) = 5.7 \pm 0.6$, which should be compared to our $\xi = -0.41^{+1.39}_{-0.57}$, and for A4 $\xi(200 - 600 \text{ km s}^{-1}) = 11.5 \pm 1.3$,

which is even more directly comparable to our $\xi = -1^{+1.75}_{-0}$. The A2 result is inconsistent at about the 4σ level, while the A4 result is discrepant by about 6σ, both in the sense that the absorbers are less clustered in adjacent sightlines than is predicted by the single-sightlines result assuming pure Hubble flow.

We confirmed that the line-of-sight clustering in our three spectra are consistent with those in the SSB sample of 55 QSOs. We constructed the C IV redshift auto-correlation function for $\Delta v < 600\ km\ s^{-1}$ along each of the three sightlines taken individually, then summed together. For all systems, one finds $\xi_{auto} = 19.8 \pm 2.4,\ 1.4^{+2.3}_{-1.3}\ 1.3^{+3.0}_{-1.5}$, and $9.7^{+17.5}_{-9.0}$, for all C IV systems, blended systems, “A2” and A4 samples, respectively, in the first 600 km s^{-1} bin. These are constructed using the average number of pairs in 600 km s^{-1} bins with 600 km s^{-1} $< \Delta v <$ 10200 km s^{-1}. These measurements are consistent with their corresponding SSB values, albeit at much poorer S/N due to the smaller number of QSO sightlines.

The inconsistency of the two-point correlation function derived from Figure 2 with that of SSB implies that single sightline correlation functions cannot be used to study the *spatial* clustering of absorbers on velocity scales of several hundred km s^{-1}. This may be due either to internal velocities within absorbers that are caused by non-gravitational processes, or by motion within gravitational potentials that have separated from the Hubble flow. These structures, either individual absorbers or clusters of absorbers, must be small enough to add little clustering power on scales of 0.5 to 1.1 h^{-1} Mpc. In either case, most of the line-of-sight correlational power is due to behavior not described by the absorber positions alone, but some peculiar motion. Line-of-sight absorber correlation functions should not be compared directly to galaxy correlation functions usually expressed as $\xi(r)$ in terms of a radial separation vector r in space.

This spatial clustering of C IV absorbers is much weaker than would be expected for

galaxies at $z = 0$. A direct comparison involves averaging the galaxy correlation function $\xi = (r/r_o)^{-\gamma}$, where we assume $\gamma = 1.8$ and $r_o = 7\ h^{-1}$ Mpc (derived from Park et al. 1994, although there are lower r_o values for different samples e.g. Fisher et al. 1994). This is averaged over a line segment extending from the tangent point at closest approach (0.512, 0.593, and 0.714 h^{-1} Mpc for each of the sightline pairs) and extending to the point at $\Delta v = 500$ km s^{-1} (1.031, 1.073, and 1.144 h^{-1} Mpc, respectively). Averaged over all three sightlines, $\bar{\xi} = 57.4$. Assumably, this can be back-evolved to $z = 2.15$ with stable hierarchical clustering formalism (Davis & Peebles 1977) if $\bar{\xi} >> 1$, according to $\bar{\xi}(z) = \bar{\xi}(0)(1+z)^{-3} = 1.84$. (Formally, this assumes $q_o = 1/2$, but remaining non-linear over all relevant z, is a close approximation for other cosmilogical densities.) Note that high-z clustering (Hudon & Lilly 1996) measured at $z = 0.48$ corresponds to $3.2 < \bar{\xi} < 7.7$, and extrapolates to $0.33 < \bar{\xi} < 0.80$ at $z = 2.15$ assuming stable clustering. These result is consistent with any of the comparable values obtained above for C IV absorbers.

Even though there are large differences between the line-of-sight clustering of the Ly α forest and C IV systems, their clustering power between different lines of sight is more similar. The strength of C IV clustering is consistent with that of the Ly α forest at similar redshifts. Crotts & Fang (1996) show, for these same sightlines at nearly the same redshift $\langle z \rangle = 2.14$, that $\xi = 0.86 \pm 0.35$ for Ly α lines with $W_o = 0.4$Å and $\Delta v < 200$ km s^{-1}. For $\Delta v < 500$ km s^{-1}, there are 51 pairs observed versus 19 expected, implying $\xi = 0.31 \pm 0.18$ (1σ). Measured in this way, it is unclear that C IV clustering is stronger than Ly α clustering. However, Ly α spatial clustering is less than the expectation for galaxies assuming stable hierarchical clustering ($\bar{\xi} = 1.61$), but not necessarily weaker than when we start from the Hudon & Lilly result.

One remaining question is whether the structure we probe on 0.5 Mpc scales might actually probe the scale of individual absorbers. We are fairly confident that this analysis

of ξ addresses more the clustering of absorbers than some measure of their characteristic size. The size of C IV absorbers is indicated by the transverse separation at which absorbers in one sightline have high probability of appearing in the adjacent sightline. For gravitationally-lensed QSOs (Steidel & Sargent 1991) and for distinct QSO pairs (Crotts et al. 1994), strong correspondence between adjacent absorption lines indicates C IV absorber sizes of only a few tens of kiloparsecs. On scales smaller than this, absorbers are presumed to merge. On scales larger than this, up to the 0.5 h^{-1} Mpc sampled by the QSO triplet, it is still possible that motion within objects that have collapsed out of the Hubble flow might still be responsible for much of the clustering signal for 200 km s^{-1} $< \Delta v <$ 600 km s^{-1} reported by SSB. Calculating $\bar{\xi}$ for the galaxy two-point correlation function at $z = 2.15$, assuming stable hierarchical clustering development, one finds $\bar{\xi} = 33$ for separations (along a sightline) of 40 h^{-1} kpc to 0.5 h^{-1} Mpc, still larger than ξ found for the A2 or A4 samples of SSB. The SSB 200-600 km s^{-1} clustering signal might plausibly be explained as clusters of absorbers smaller than 0.5 h^{-1} Mpc with internal velocities of a few hundred km s^{-1}. Indeed, high resolution simulations of fragments collapsing ultimately into galaxies at $z \approx 0$ show that these fragments at $z \approx 3$ subtend such spatial scales e.g. Rauch, Haehnelt & Steinmetz (1997).

These conclusions are based on a single group of sightlines, and such close groupings of reasonably bright, sufficiently high z QSOs are extremely rare. Nonetheless, a larger sample to check and refine these conclusions is desired.

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Figure 1 shows a complex $z \approx 2.24$, C IV doublet from KP 78, fit by 10 Voigt components.

Figure 2 shows the cross-correlation between pairs of the three sightlines, for three restricted samples: all systems after blending within 200 km s^{-1} (dashed curve), blended systems with rest equivalent width $W_o > 0.10$ for C IV $\lambda1548$, in close analogy to SSB sample A2 (horizontally-striped bars), and blended systems with rest equivalent width $W_o > 0.15$, as in SSB sample A4.

Table 1. C IV ABSORPTION SYSTEMS FOUND IN QSO TRIPLET 1623+27

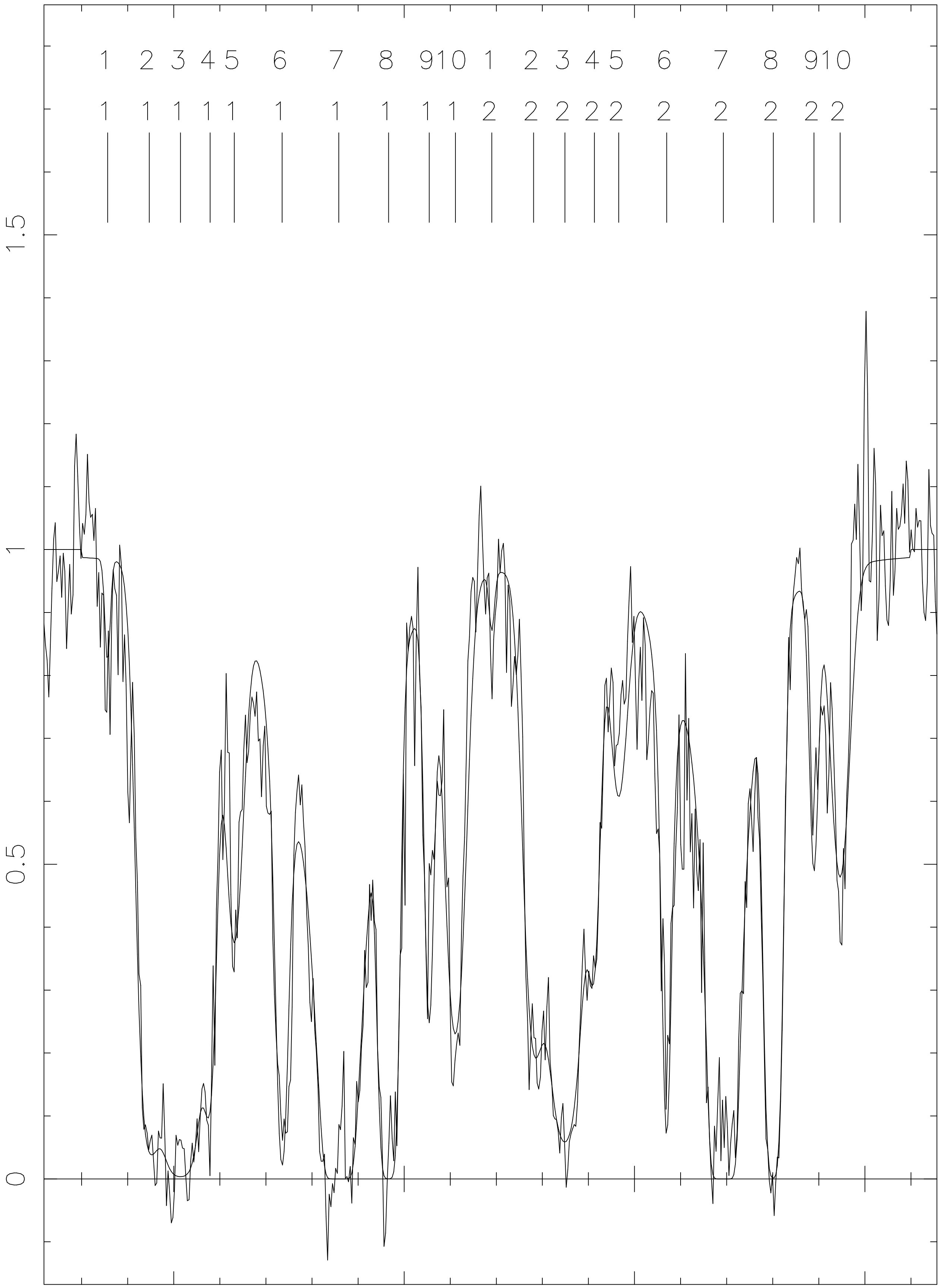
QSO	Blended System z	C IV λ1548 Rest EW, W_o (Å)	Component Redshifts
KP 76	1.845177	0.055 ± 0.006	1.845177
	2.112378	0.313 ± 0.007	2.111746, 2.112022, 2.112872
	2.156867	0.071 ± 0.008	2.156484, 2.157249
	2.245817	0.178 ± 0.008	2.245372, 2.246084, 2.246438
KP 77	1.878027	0.070 ± 0.003	1.878027
	1.880660	0.144 ± 0.003	1.880084, 1.881235
	1.972602	0.124 ± 0.004	1.972276, 1.972929
	2.050746	0.662 ± 0.006	2.049659, 2.049868, 2.050201, 2.051020, 2.051807, 2.052194
	2.052938	0.487 ± 0.006	2.052644, 2.052866, 2.053120
	2.161619	0.307 ± 0.005	2.161104, 2.161317, 2.161332[a], 2.162024
	2.244602	0.099 ± 0.003	2.244602
	2.400640	0.307 ± 0.005	2.399910, 2.400782, 2.401035, 2.401195, 2.401791
	2.444659	0.087 ± 0.005	2.443576, 2.444170, 2.445444
	2.528857	0.153 ± 0.003	2.528504, 2.529211
KP 78	1.985477	0.197 ± 0.006	1.985368, 1.985587
	2.042732	0.155 ± 0.008	2.042464[b], 2.043000
	2.061465	0.151 ± 0.005	2.061347, 2.061583
	2.094603	0.912 ± 0.004	2.093318, 2.094057, 2.094360, 2.095019, 2.095867
	2.097187	0.103 ± 0.003	2.097187
	2.115063	0.112 ± 0.005	2.115063
	2.240122	1.620 ± 0.012	2.238328, 2.238913, 2.239351, 2.239765, 2.240104, 2.240775, 2.241570, 2.242268, 2.242837, 2.243204
	2.550918	0.131 ± 0.004	2.550744, 2.551092

[a]apparent broad component, b value uncertain

[b]highly asymmetric line

Table 1—Continued

QSO	Blended System z	C IV λ1548 Rest EW, W_o (Å)	Component Redshifts



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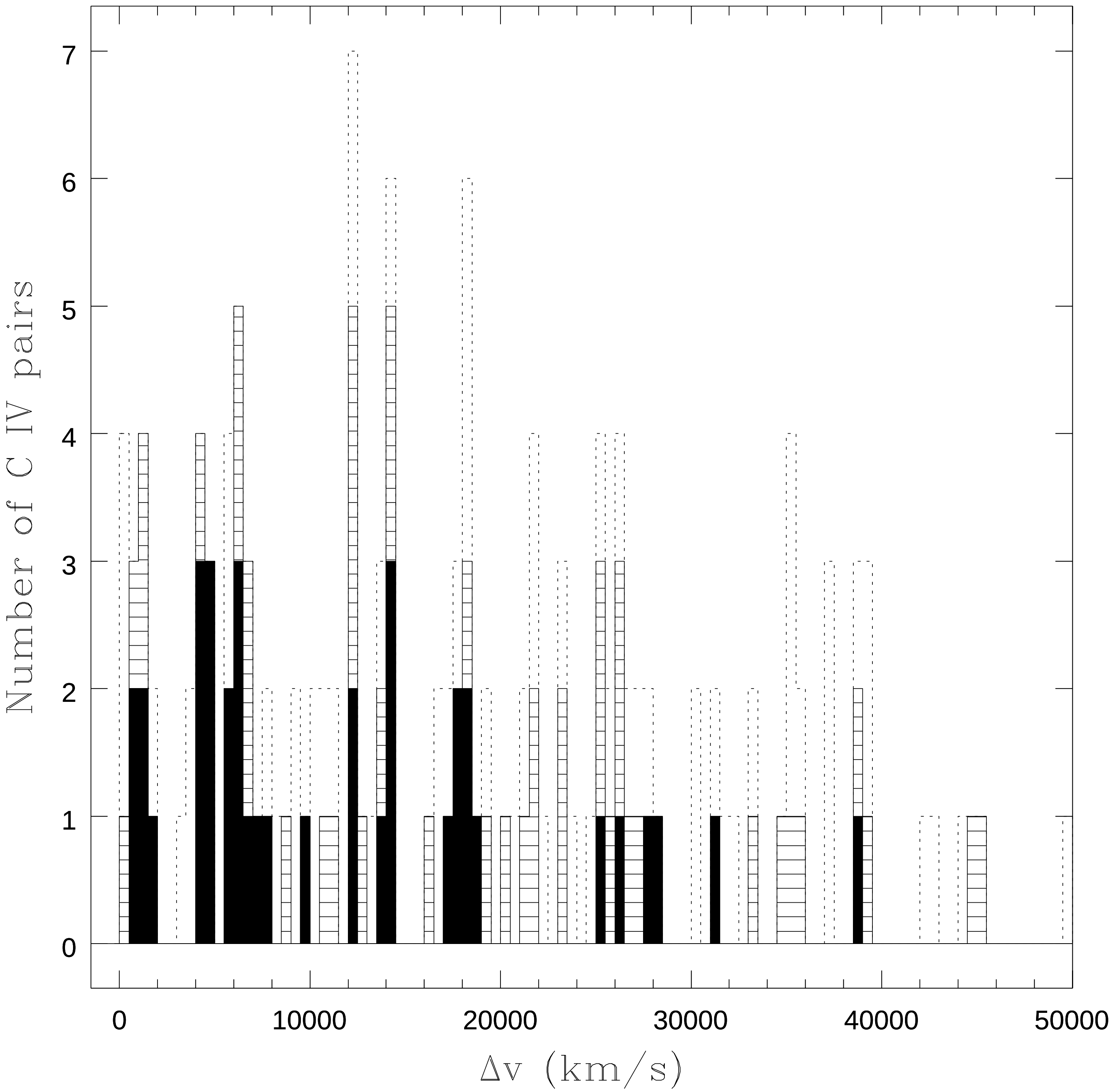
0
5015
5020
5025
5030



Number of C IV pairs
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1
2
3
4
5
6
7
0
10000
20000
30000
40000
50000
Δv (km/s)